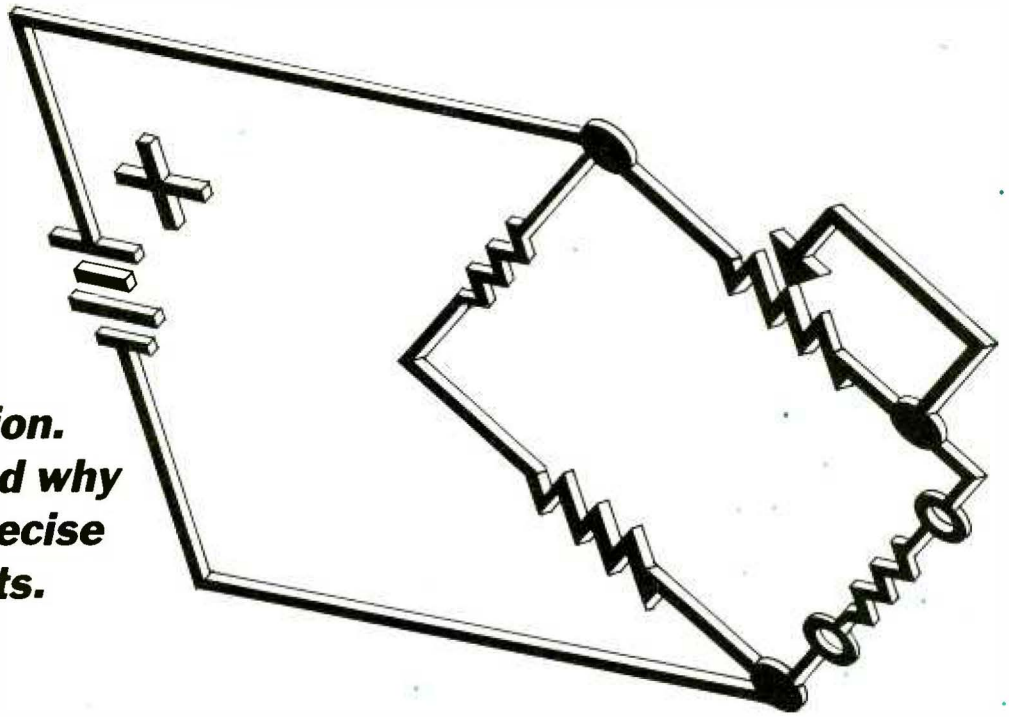
The bridge circuit holds an honored place in the history of electronic instrumentation. Learn how and why they make precise measurements.



BRIDGE CIRCUITS

RAY MARSTON

A BRIDGE CIRCUIT IS AN INSTRUMENT for making *comparison measurements*. These circuits are widely used to measure resistance, inductance, capacitance, and impedance. They have four sections or arms connected in series to form a diamond. An AC or DC voltage source is connected between one pair of opposite junctions, and an indicating meter or output circuit is connected between the other pair of opposite junctions.

Bridge circuits operate on a *null-indication* principle. When the bridge is balanced, the output is zero. Consequently, the indication is independent of the calibration of the indicating device. For this reason, accurate measurments can be made with bridges. Bridge circuits can also control other circuits. When functioning as controls, one arm of the bridge contains a resistive element that is sensitive to such physical variables as temperature or pressure.

Bridge circuits are classical electrical measuring instruments predating electronics as a field distinguished from classical electrical engineering. Until about 25 years ago, bridge circuits were the only practical instruments for making many kinds of precise measurements.

However, in many applications they have been displaced by digital multimeters that contain provisions for making comparable measurements. Nevertheless, the availability of low-cost digital multimeters and capacitance meters (sometimes combined in one instrument) does not negate the value of the basic bridge circuit.

The Wheatstone bridge

The Wheatstone bridge is the best known bridge circuit and the one most widely taught in electronics courses. It consists of two parallel resistance branches with each branch containing two series elements, typically resistors. A DC voltage source is connected across a diamond-shaped network to provide a source of current through the network. A *null detector*, originally a simple galvanometer, is connected between the parallel branches to detect a condition of balance.

The circuit shown in Fig. 1 was first invented by S.H. Christie in 1833. However, its value was not recognized until 1847 when Sir Charles Whetstone described how it could make accurate electrical measurements. As a result of his insights and demonstrations, the bridge came to be known as the Wheatstone bridge.

The Wheatstone bridge has probably been in use longer than any other electrical measuring instrument. Although still an accurate and reliable instrument, it is not as convenient to use as the new digital multimeters. Nevertheless, 0.1% accuracy is commonly obtainable with the Wheatstone bridge. This compares with the 3% to 5% error expected in resistance measurements made with analog ohmmeters. Accuracy on digital multimeters will depend on the meter's

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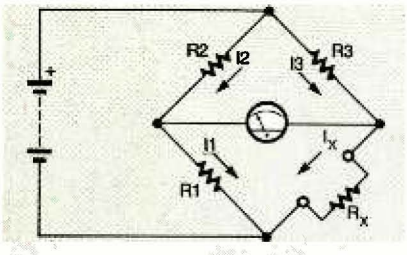
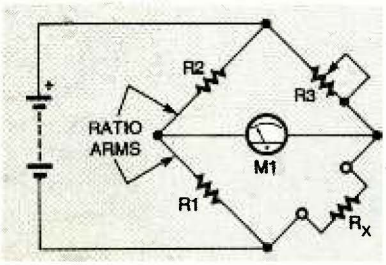


FIG. 1—ORIGINAL WHEATSTONE bridge as demonstrated by Sir Charles Wheatstone in 1843.

TABLE 1
RESPONSE OF 6-RANGE WHEATSTONE BRIDGE

Switch S1 Range	Bridge Range (Ohms)	Resistor R1 Value (Ohms)	R1/R2 Ratio (Nominal)	Bridge Null Sensitivity
1	0-10	10	1/1000	3.0 %
2	0-100	100	1/100	0.3 %
3	0-1k	1k	1/10	0.03 %
4	0-10k	10k	1/1	0.003 %
5	0-100k	100k	10/1	0.03 %
6	0-1MEG	1MEG	100/1	0.3 %



FIG, 2—CONTEMPORARY VERSION of the Wheatstone bridge.

characteristics, such as DC voltage accuracy and resolution.

When making measurements with a Wheatstone bridge to determine the value of an unknown resistor (R_X) one of the remaining resistors is varied until the current through the null detector decreases to zero. The bridge is then in a balanced condition. This means that the voltage across resistor R3 is equal to the voltage drop across the unknown resistor R_X and the two divider resistors R1 and R2 are passing equal voltages. As a result, the following is true:

(1) $I1 \times R1 = I_X \times R_X$

At balance the voltage drops across R2 and R3 are equal so:

(2) $I2 \times R2 = I3 \times R3$

Because no current flows through the galvanometer G when the bridge is balanced, it follows that:

(3) $I2 = I1$ and $I3 = I_X$

Substituting I2 for I1 and I3 for I_X in equation 1 yields the following equation:

(4) $I2 \times R1 = I3 \times R_X$

Dividing equation 2 by equation 4, yields.

(5) $R2/R1 = R3/R_X$

This can be rewritten as:

(6) $R2 \times R_X = R3 \times R1$

Equation 6 states the conditions of balance of a Wheatstone bridge and is useful for computing the value of an unknown resistor, once balance has been achieved.

Dividing both sides by R1 yields the most common Wheatstone bridge equation:

$R_X = R3 \times R1/R2$

An important feature of the original Wheatstone bridge was its very high null sensitivity. Thus, if the bridge is energized from 10-volt DC, 5 volts is developed across all resistors at balance, and the galvanometer remains centered. A shift of only 0.1% will then give a 5 millivolt reading on a calibrated moving-coil analog meter. By installing a simple null-detecting DC amplifier, this circuit can have a *null sensitivity* factor (i.e., percentage out-of-balance detection value) of about 0.003%.

However, the major drawback of this 1847 bridge is that R3 must have a large resistive range if it is to balance all possible values of R_X. In 1848, the German-born engineer Wilhelm von Siemens, overcame this drawback by introducing the modifications, as shown in Fig.2

The bridge can be further modified as shown in Fig. 3 by giving R2 a fixed value and making R1 switch-selectable. This version is based on a 1970 version, high-accuracy laboratory measuring instrument.

The circuit in Fig. 3 can measure DC resistances from near-zero to 1 megohm in six switch-selected decade ranges. Resistor R3 is a calibrated 10-kilohm variable potentiometer that controls the sensitivity of the balance-detecting center-zero meter. The value of RL limits its bridge current to a few milliamperes. Table 1 lists the major weakness of this 1970 Wheatstone bridge—its null sensitivity (which is proportional to the R_X test voltage) degrades in proportion to the R1/R2 ratio's divergence from unity.

Consequently, the sensitivity is nominally 0.003% on the 10-kilohm range where the R1/R2 ratio is 1/1, but it degrades to

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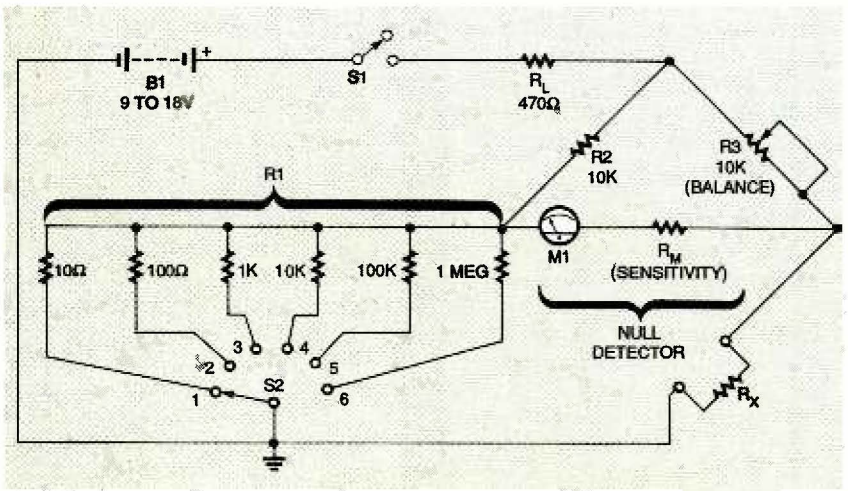

FIG. 3—WHEATSTONE BRIDGE with six DC measuring ranges.

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BRIDGE CIRCUITS

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0.3% on the 100-ohm and 1-megohm ranges where the R1/R2 ratios are 1/100 and 100/0, respectively. To be a practical instrument, the Fig. 3 circuit must include a sensitive null-balance detector.

Figure 4 is a schematic for a ×10 DC differential amplifier for use with an external analog volt-ohmmeter to form such a detector. This circuit must have its own own independent 9-volt power supply. The LF351 is a low-cost BIFET operational amplifier available from Motorola, Texas Instruments, National Semiconductor, and others.

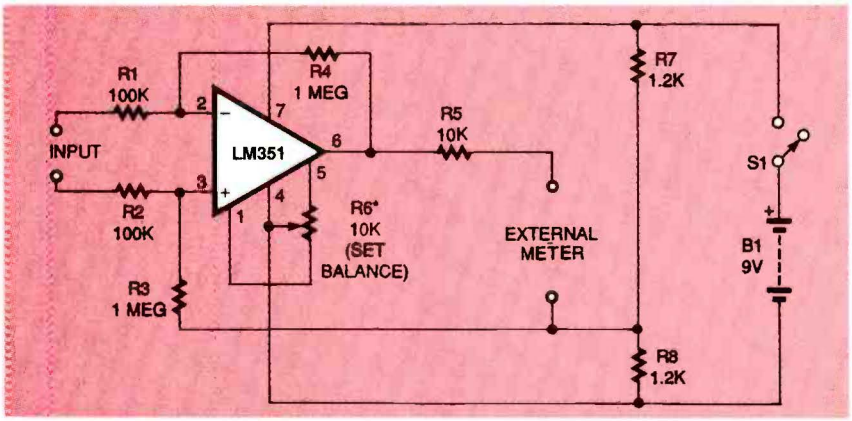

FIG. 4—A DC NULL POINT AMPLIFIER for use with an external digital multimeter or analog volt-ohmmeter

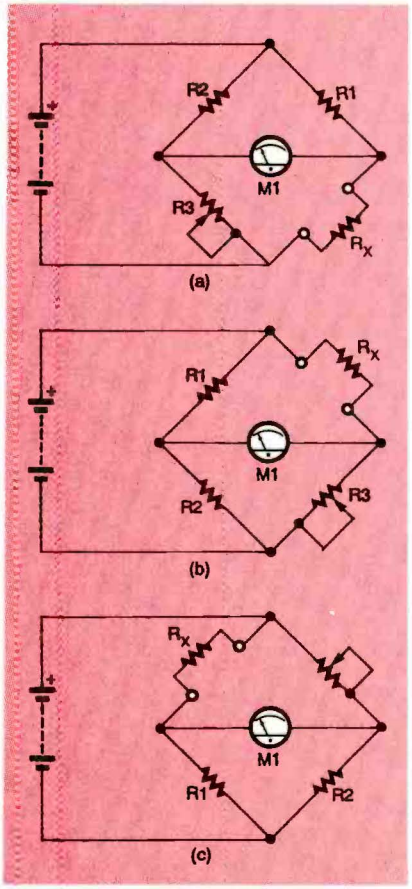

FIG. 5—THREE ALTERNATIVE VERSIONS of Wheatstone bridges follow the same rules as the circuit in Fig 2.

Wheatstone variations

The Wheatstone bridge circuit of Fig. 2 can be configured in three other ways without invalidating the basic balance equations, as shown in Figure 5. In each form R1/R2 are known as the bridge's ratio arms. Notice that the bridge's signal-source and detector terminals can be transposed without upsetting the ciruit's balance equations. This also holds true for the various versions of capacitance and inductance bridges. The most useful Wheatstone bridge variation is that shown in Fig. 5-a.

Figure 6 shows a modern six-ampere or 100-microampere range for high-sensitivity. In the 100-microampere range, the circuit must first be balanced by short-circuiting its input terminals together and trimming the multiturn 10-kilohm SET-BALANCE control for a zero reading on the meter.

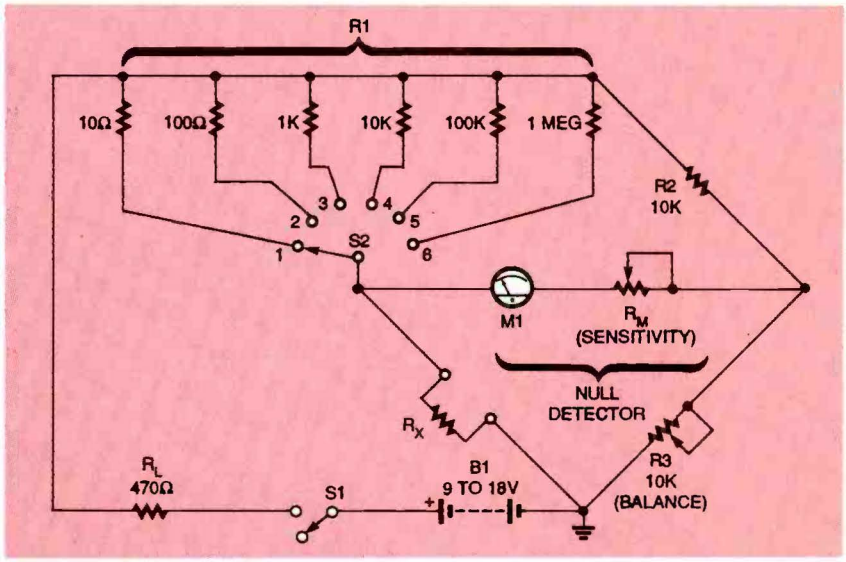

FIG. 6—HIGH-SENSITIVITY, SIX RANGE Wheatstone DC resistance-measuring bridge.

The LF351 has a JFET input for low input offset voltage and BIFET technology provides wide bandwidth and fast slew rates with low bias currents as well as low input offset currents and supply currents. It is the functional equivalent of the LF353, and the LF347 is a dual version.

An external volt-ohmmeter can be set to its 2.5-volt DC range for low-sensitivity measurements, or to its 50-microampere range version of this circuit, and Table 2 lists its benefits over the circuit in Fig. 3. Its null sensitivity (which is proportional to the R3/R2 ratio at balance) is very high on all ranges, and varies from 0.003% at R3's full scale balance value, to 0.03% at one-tenth of full scale.

By confining all measurements to the top nine-tenths of the R3 range, one can measure all resistance values in the 1-

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TABLE 2
RESPONSE OF 6-RANGE HIGH-SENSITIVITY BRIDGE

Switch S1 Range	Bridge Range	Resistor R1 Value (Ohms)	R1/R2 Ratio (Ohms)	Bridge Null Sensitivity (Nominal)
1	0-10	10	1/1000	Proportional
2	0-100	100	1/100	to value of R3
3	0-1k	1k	1/10	to 0.003% at
4	0-10k	10k	1/1	full scale on
5	0-100k	100k	10/1	all ranges
6	0-1MEG	1MEG	100/1	

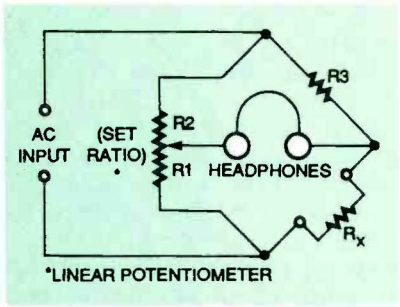

FIG. 7—AC POWERED Wheatstone bridge with variable ratio-arm balancing and headphone-detection.

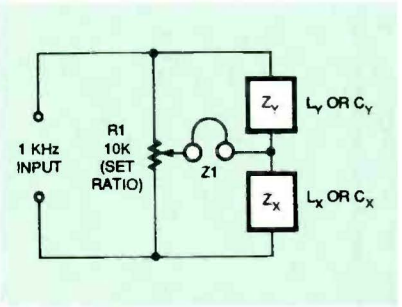

FIG. 9—WHEATSTONE BRIDGE for determining both capacitive and inductive reactances.

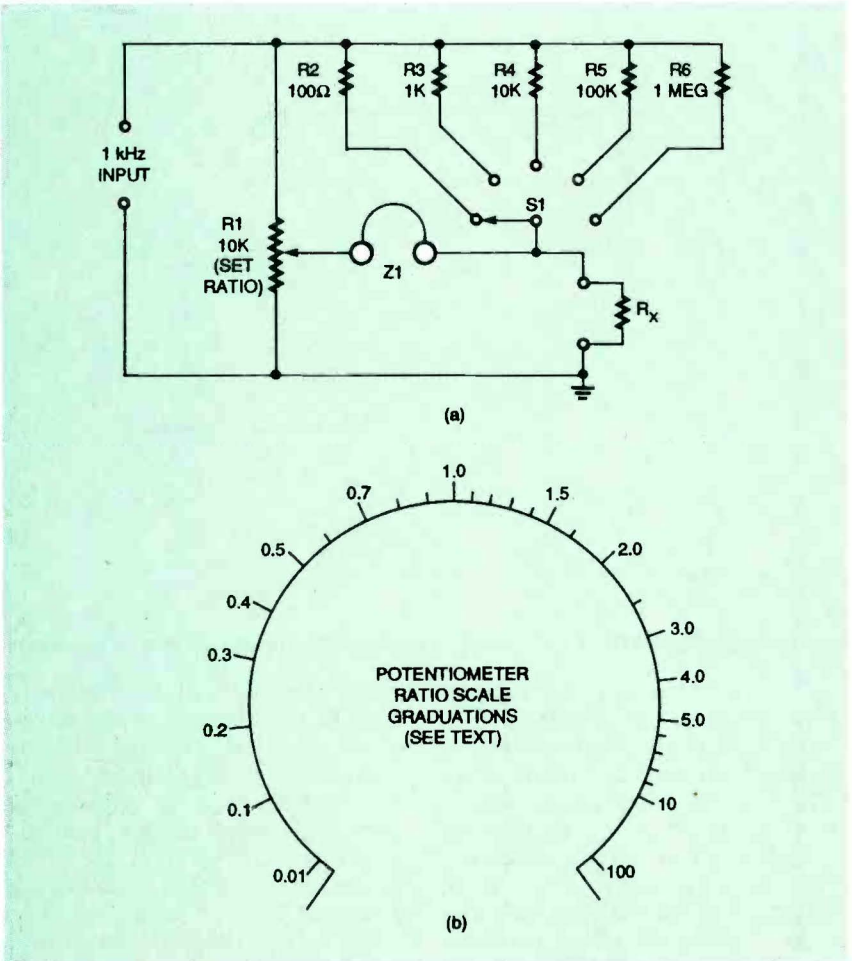

FIG. 8—FIVE-RANGE resistance bridge, with rotary panel potentiometer scale markings (*a*) and typical ratio scale markings (*b*).

ohm to 1-megohm range with excellent null sensitivity.

A Wheatstone bridge can be energized from either an AC or DC source without altering the fundamentals of its operation. Figure 7 is the circuit for an AC-energized Wheatstone bridge whose balance condition is maintained with an infinitely-variable pair of "ratio" arms consisting of potentiometer R1 which provides the resistive values of R1 and R2.

The sum of the resistive values of R1 and R2 equals the resistive value of potentiometer. The balance sensitivity of this circuit is high enough to permit detection with headphones.

Figure 8 shows a five-range version of the Wheatstone bridge circuit of Fig. 7. It covers a resistive range of near-zero to near-infinite ohms with its highest precision between 10 ohms and 10 megohms. Rotary panel potentiometer R1's ratio equals one when its wiper is at midrange. The diagram shows expected typical scale graduations for a calibrating this control potentiometer. These must be manually marked as described later in this article.

To measure with the Fig. 8 circuit, connect the bridge to a 1-kHz sinewave generator, insert the unknown resistor R_X, and adjust rotary switch S1 and rotary panel potentiometer R1 until a null can be detected by listening with the headphones. When that occurs, the value of resistor R_X equals the value of the resistor connected to S1 multiplied by the scale value on potentiometer R1. A balance can be obtained on any range, but for the highest precision, the balance should occur with an R1 scale reading between about 0.27 and 3.0.

To calibrate the scale of panel potentiometer R1, insert a 10-kilohm, 1% resistor in the R_X position. Then index rotary switch S1 progressively through its 100-ohm, 1-kilohm, 10-kilohm, 100-kilohm, and 1-megohm positions. Mark the scale at each sequential balance point as 0.01, 0.1, 1.0 (midscale), 10, and 100.

Repeat this procedure with

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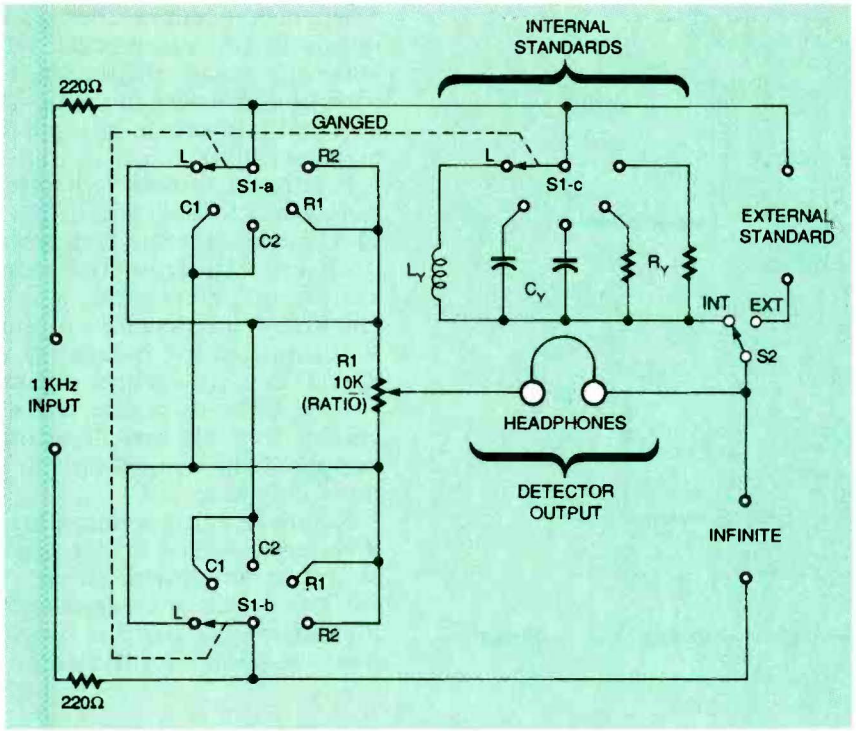

FIG. 10—LCR BRIDGE with headphone null detector.

R_X values that are multiples or submultiples of 1.5, 2, 3, 4, 5, etc., until the scale is completely calibrated, as shown in Fig. 8-b.

Resolution and precision

There are four important quality characteristics of a measurement bridge: (1). measurement range, (2) balance-sensitivity, (3) resolution, and (4) precision. The term resolution refers to the accuracy with which the R_X value can be read from the bridge's controls. For example, in Figs. 3 and 6, R3 gives a resolution of about 1% of full-scale if it is a manually-calibrated, linear, potentiometer, or about 0.005% of full-scale if it includes a four-decade resistor box.

The resolution of the bridge in Fig. 8 varies from ±1% at a "1" ratio to ±2% at a 0.3 or 3.0 ratio, to ±5% at a 0.1 or 1.0 ratio.

The term precision refers to the basic accuracy of the bridge, assuming that it has perfect balance-sensitivity and resolution, and equals the sum of the R1/R2 ratio tolerance and the tolerance of the resistance standard R3. If the R1/R2 ratio is set strictly by precision resistors, the ratio's precision equals the sum of the R1 and R2 tolerances. However, there are other techniques that permit resistors to be matched so that ratio errors are reduced to only about ±0.005%.

TABLE 3
STANDARDS VS. BRIDGE VALUE

	Standards Value	Bridge Range
R3	100 Ω 100 k 1 MEG	10 Ω-1 k 1 k-100 k 100 k-10 MEG
C3	100 pF 0.01 µF 1 µF	10 pF-0.001 µF 0.001 µF-0.1µF 0.1 µF-10 µF
L3	1 mH 100 mH 10 H	100 uH-10 mH 10 mH-1 H 1 H-100 H

For example, if the high-resolution Wheatstone bridge in Fig. 6 is made with R1 and R2 as 1% resistors and R3 is a manually-calibrated control potentiometer, the circuit will have a basic precision of only 3%. However, if the values of R1 and R2 are correctly matched, the precision of the bridge increases to ±1.005%.

The circuit's precision can be increased to ±0.105% with a ±0.1% multidecade resistor box in the R3 position. Bear in mind that additional errors can creep in when you are measuring very low or very high resistance values. The most likely cause will be the resistance values of switch contacts and leads when measuring low resistive values, and leakages when measuring high values.

The overall quality of a bridge depends on its balance-sensitivity, resolution, and precision. Thus, the circuit in Fig. 6 offers excellent sensitivity and very good resolution and precision. Consequently, it can function as the basic circuit of either an inexpensive, simple bench test instrument or as a component in a precision laboratory instrument, depending on how it is built.

By contrast, the bridge in Fig. 8 has intrinsically poor resolution and precision. This means that it is suitable only for fast, imprecise measuments such as might be satisfactory for servicing equipment.

Capacitance and inductance

An AC-energized Wheatstone bridge can measure reactance, resistance, capacitance (C) and inductance (L). The circuit in Fig. 9 is a modification of the circuit in Fig.7 to measure C or L values by replacing R4 and R_X with comparable reactances. This will work if C_X or L_X are reasonably pure and have 1-kHz impedances greater than about 1 ohm and less than 10 megohms.

The difficulty in trying to measure inductance with this circuit is that accurate inductors (for use in the Z4 position) are hard to find, and inductive impedances are only 6.28 ohms per millihenry at 1 kHz.

The only difficulty in measuring capacitance is that the C_X value is proportional to the reciprocal of potentiometer R1 resistance scale markings. If the basic bridge is to measure both R and C, two calibrated sets of potentiometer R1 scales are needed. This drawback can be overcome by fitting R1 with a reversing switch. An example of this is shown as the multirange LCR bridge of Fig.10. Thus, only a single scale as

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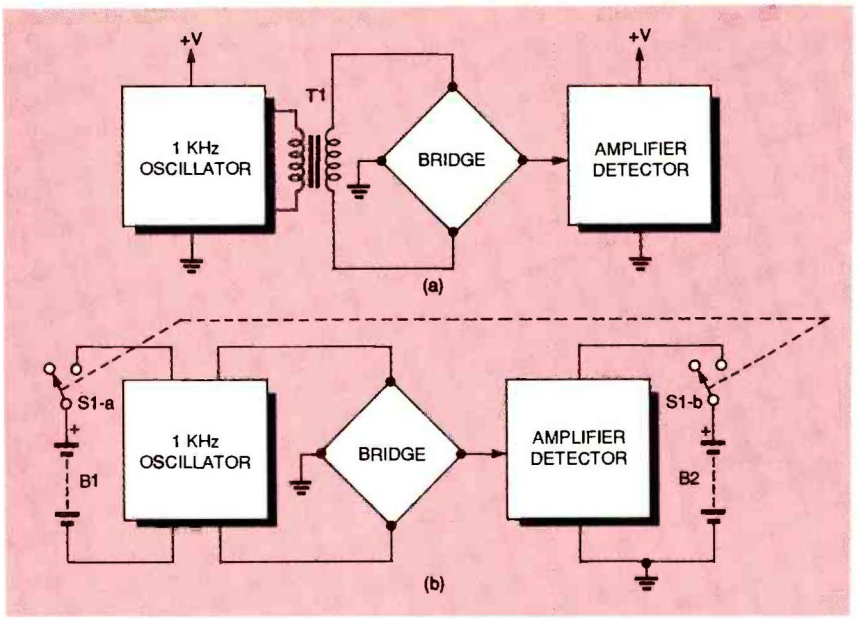

FIG. 11—ALTERNATIVES CIRCUITS for powering and detecting nulls in Wheatstone bridge circuits.

When that occurs, the C_X value equals 100 nanofarads. This 100-nanofarad standard can then be connected to the bridge and used to create a 1 microfarad standard.

Figure 11 shows two alternative block diagrams. Figure 11-a, the first option, is to power both circuits from the same supply but to isolate the oscillator by transformer-coupling its output to the bridge, as in Fig. 11-a. The second option, Fig. 11-b, is to power the oscillator from its own "floating" supply. This second option is more efficient.

Figure 12 is the schematic for a battery-powered bridge power source. It can provide either a 9-volt DC output or an excellent 1-kHz sinewave output with a peak-to-peak amplitude of 5 volts. The oscillator is a diode-stabilized Wien bridge oscillator that works from a split power supply derived from the battery through resistors R1 and R2.

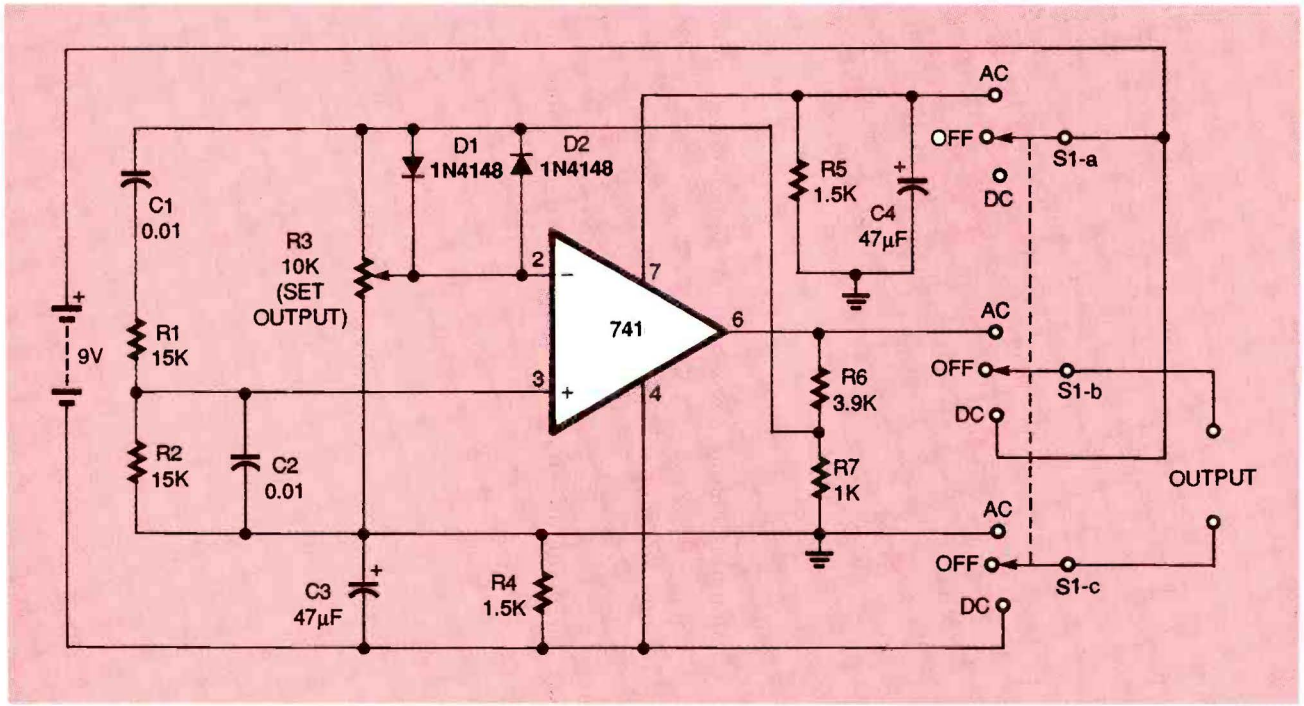

FIG. 12—POWER SOURCE for bridge circuits capable of 9-volt DC and 5-volt, 1-kHz outputs.

shown in Fig. 8 is required.

The general purpose LCR bridge with headphone detector shown in Fig. 10 is a versatile instrument. Switch S2 permits it to be used with either internal or external L, C, or R standards. The midscale value of each range is equal to the value of the standard assigned for that range, as listed in Table 3.

When this instrument is calibrated, it can be help to create its own alternative measurement standards. For example, if an accurate 10-nanofarad capacitance standard is inserted across the EXTERNMAL STANDARD terminals, a 100-nanofarad standard can be created by moving potentiometer R1 to the "10" position and then connecting capacitors in parallel across the "X" terminal for a null balance.

The circuit has a low-impedance output, and consumes a less than 4 milliamperes of quiescent current. To set up the oscillator, connect its output to a suitable oscilloscope and trim potentiometer R1 to give a reasonably pure sinewave output of about 5 volts, peak-to-peak. Ω

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